A COMPARISON OF HUMAN AND ROBOTIC SERVICING OF THE HUBBLE SPACE TELESCOPE

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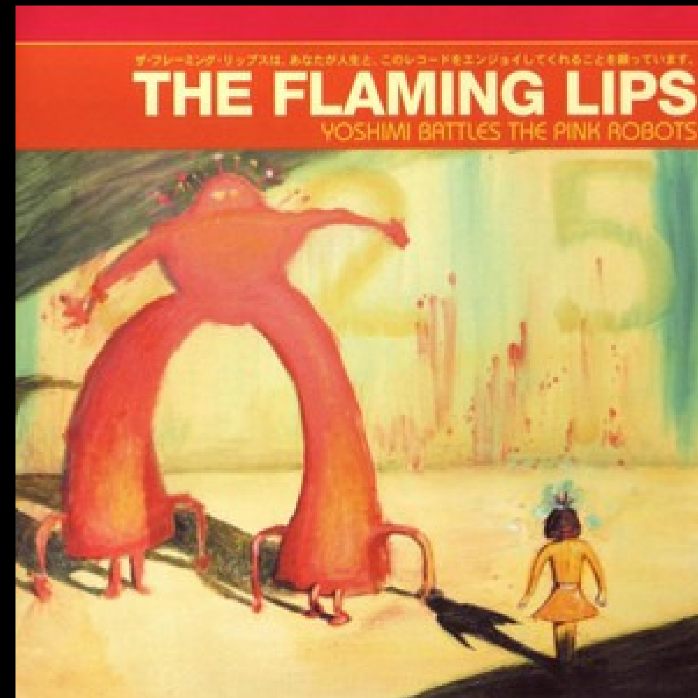
Preface



- This talk <u>is not</u>:
  - A humans vs. robots contest
  - About what could we do with *tomorrow's* robots or manned missions
  - A cost comparison
  - The result of a hypothetical study
- This talk <u>is</u> intended to offer some lessons learned from an actual servicing mission that was worked *hard* for *both* a human and robotic implementation
- *Views and opinions expressed in this talk are those of the author alone, and do not represent the official positions of any organization or company, including the Hubble Space Telescope Program or NASA*

Outline

- SM4 Background
- Interfaces
- Tools
- Mission Duration
- Flexibility
- Adaptability
- Conclusions

SM4 BACKGROUND

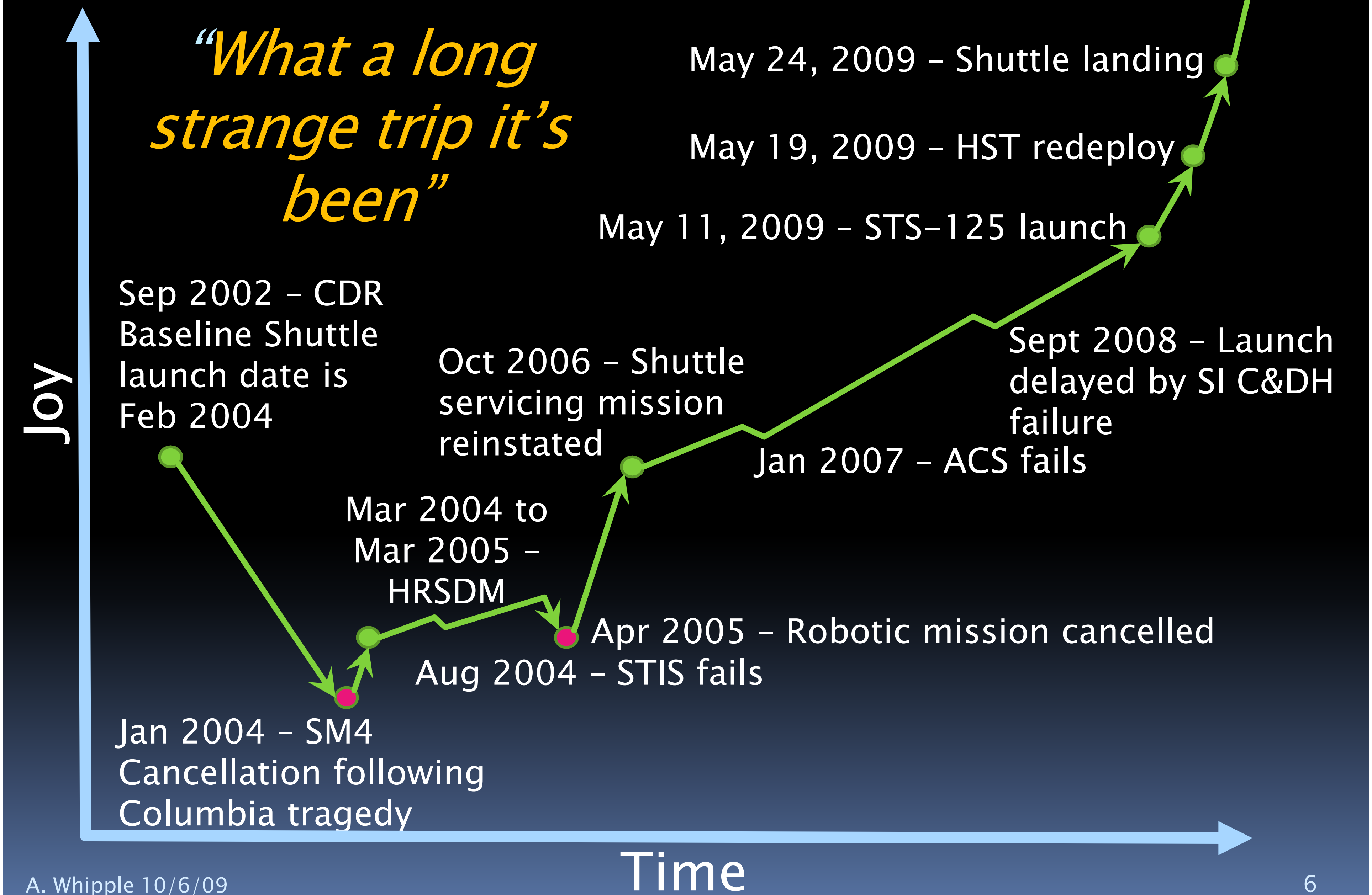
HST as last seen in 2002

Origins of Servicing Mission 4 (SM4)

- Planning for SM4 goes back at least to 1996
  - Last planned shuttle servicing mission to Hubble
  - AO that led to selection of Cosmic Origins Spectrograph (COS) released in Nov 1996
  - Wide Field Camera 3 (WFC3) started in 1997
  - Servicing Mission 3 conducted in March 2002
- Critical Design Review conducted in Sept 2002
  - Baselined manifest (in priority order):
    - 3 Rate Sensing Units (RSUs – 2 gyros each)
    - 2 Battery Module Assemblies (BMAs – 3 batteries each)
    - COS
    - WFC3
    - Aft Shroud Cooling Systems (ASCS)
    - New Outer Blanket Layer 7,8 (NOBLs)(Multi Layer Insulation repair)
    - Fine Guidance Sensor 3R (FGS3R)
    - DMU to SIC&DH Cross-Strap (DSC) unit
    - NOBL5
    - Reboost

Evolution of SM4

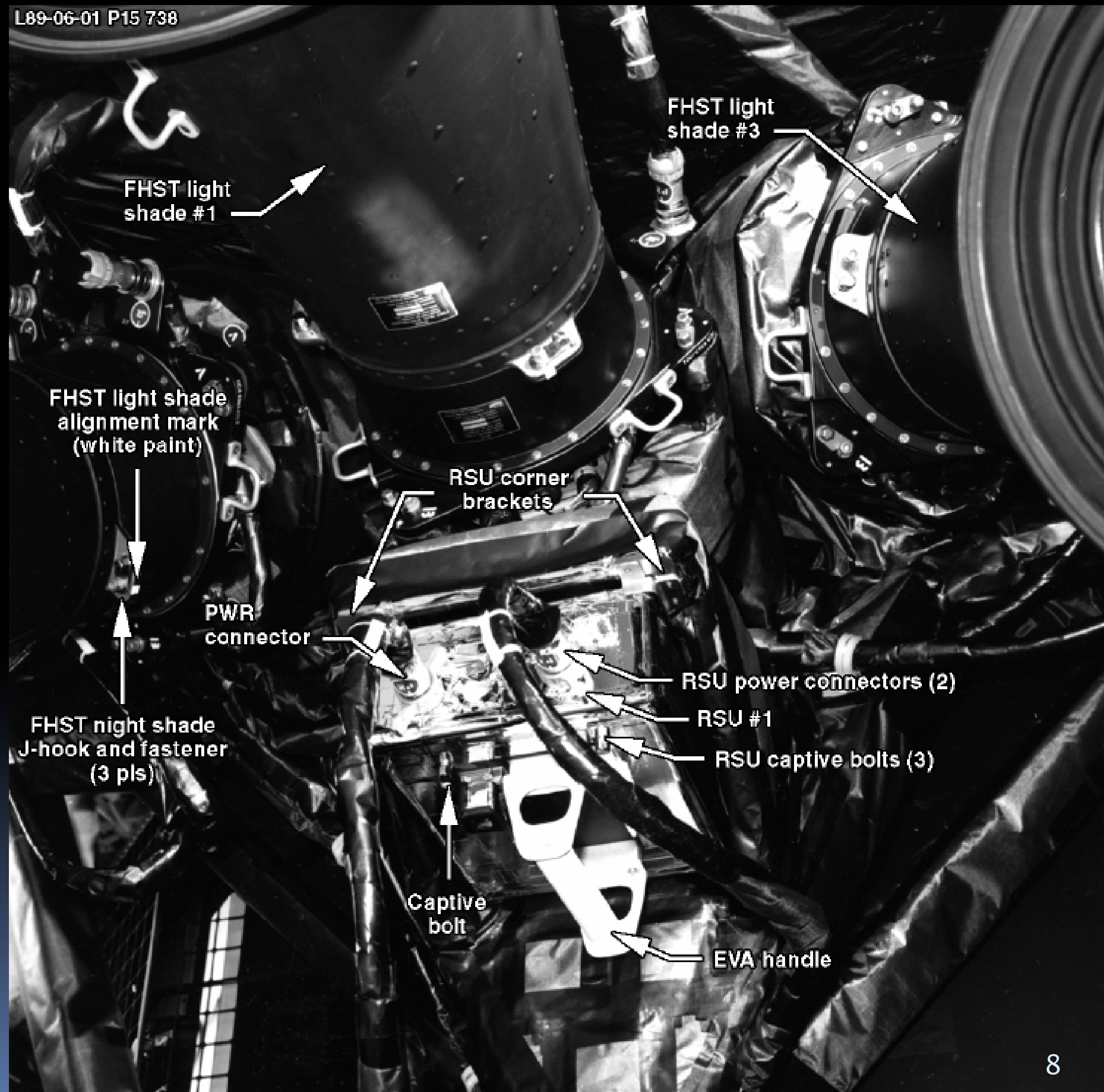
"What a long strange trip it's been"



Hubble Robotic Servicing and De-orbit Mission

- HRSDM was worked *hard* for just over a year
- Incorporated modified shuttle arm and ISS Dextre robot
- 1000+ person team
  - GSFC, Lockheed, Ball, Draper, Orbital, Jackson & Tull, Aerojet, MDRobotics, STScI, UMD, JSC, KSC, MSFC, JPL, CSA, ESA
- Scrutinized
  - 21 member IPAO Review Team
  - 19 member GSFC Review Board
  - 53 reviews (including peer)
  - 912 RFAs (514 closed by cancellation)
- April 2008 planned launch date
- Carried through an extremely successful PDR
- Terminated in April 2005 due to cost and development risk and renewed possibility of shuttle-based SM4

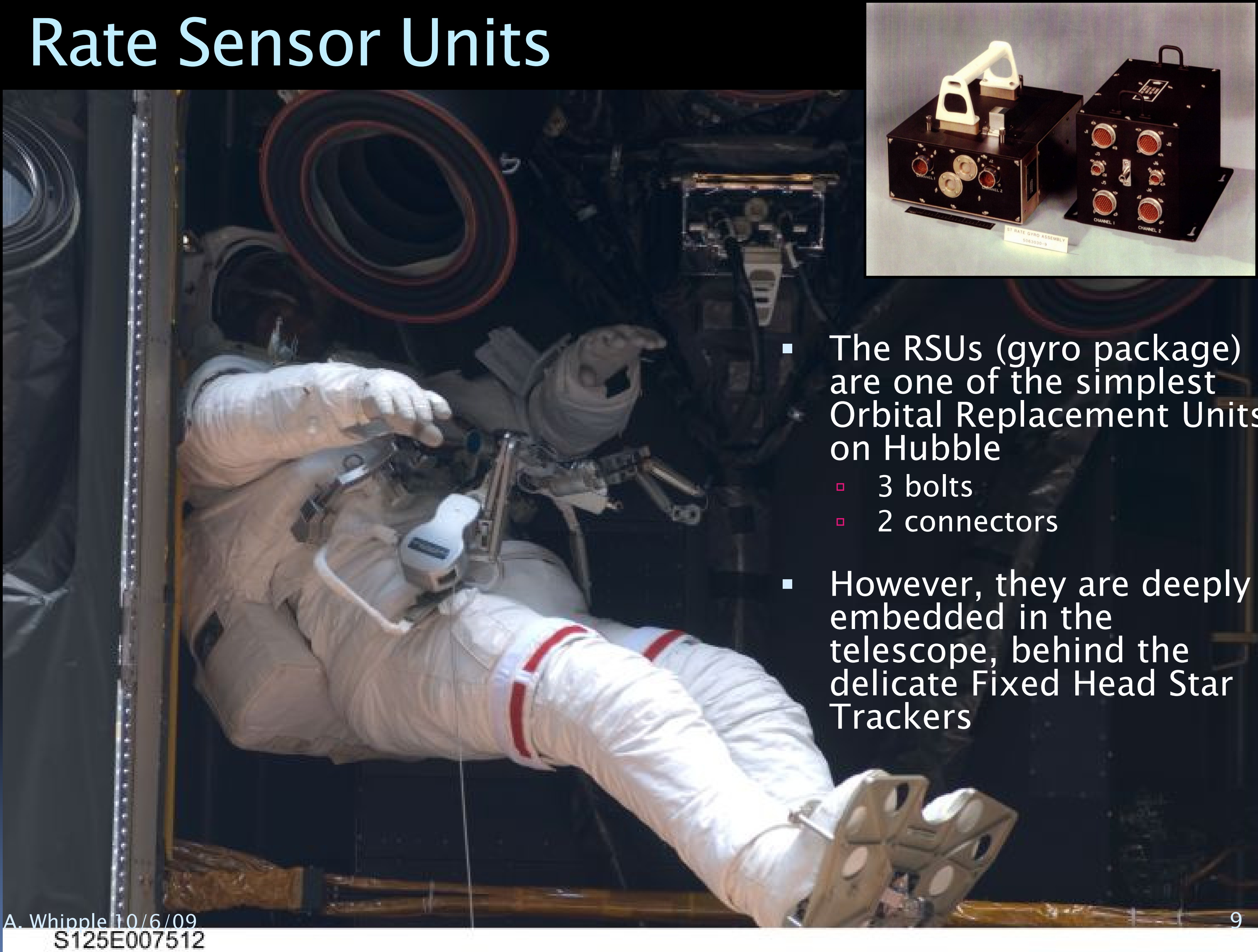
INTERFACES



Gyro location on HST

A. Whipple 10/6/09

Rate Sensor Units

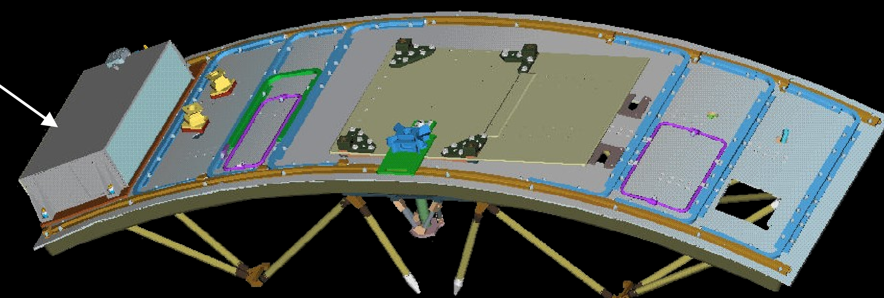


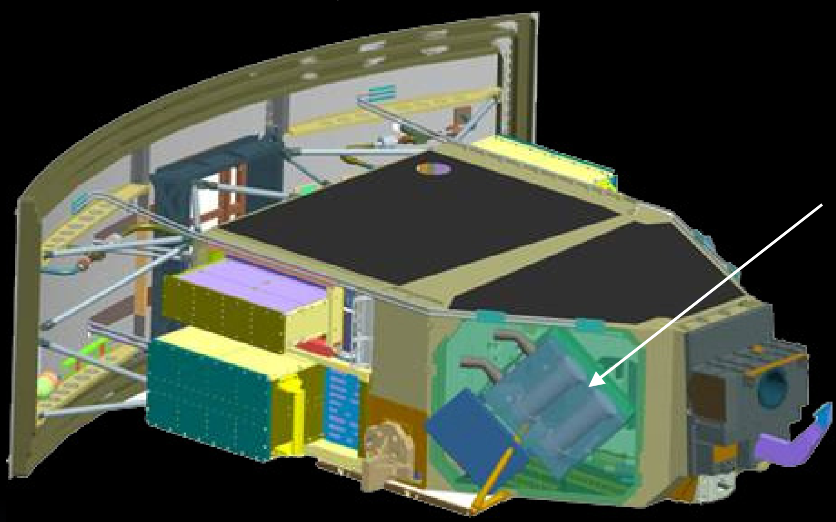
- The RSUs (gyro package) are one of the simplest Orbital Replacement Units on Hubble
  - 3 bolts
  - 2 connectors
- However, they are deeply embedded in the telescope, behind the delicate Fixed Head Star Trackers

Human installation of RSUs

- Six astronauts have changed out 8 RSUs on three servicing missions:
  - STS-61 (SM1, 1993) – RSUs 2 & 3
  - STS-103 (SM3A, 1999) – RSUs 1, 2 & 3
  - STS-125 (SM4, 2009) – RSUs 1, 2 &3
- Despite continuing improvements in tools and training, problems were encountered on each mission and with different RSUs in all three positions

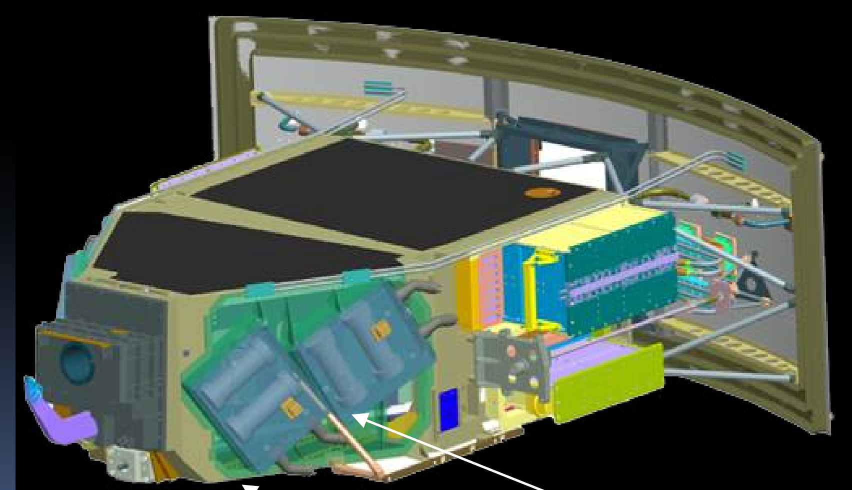
HRSDM WFC3 RSU Accommodation





3 HST Rate Sensor Units (RSU's) Located on the WFC3 Enclosure

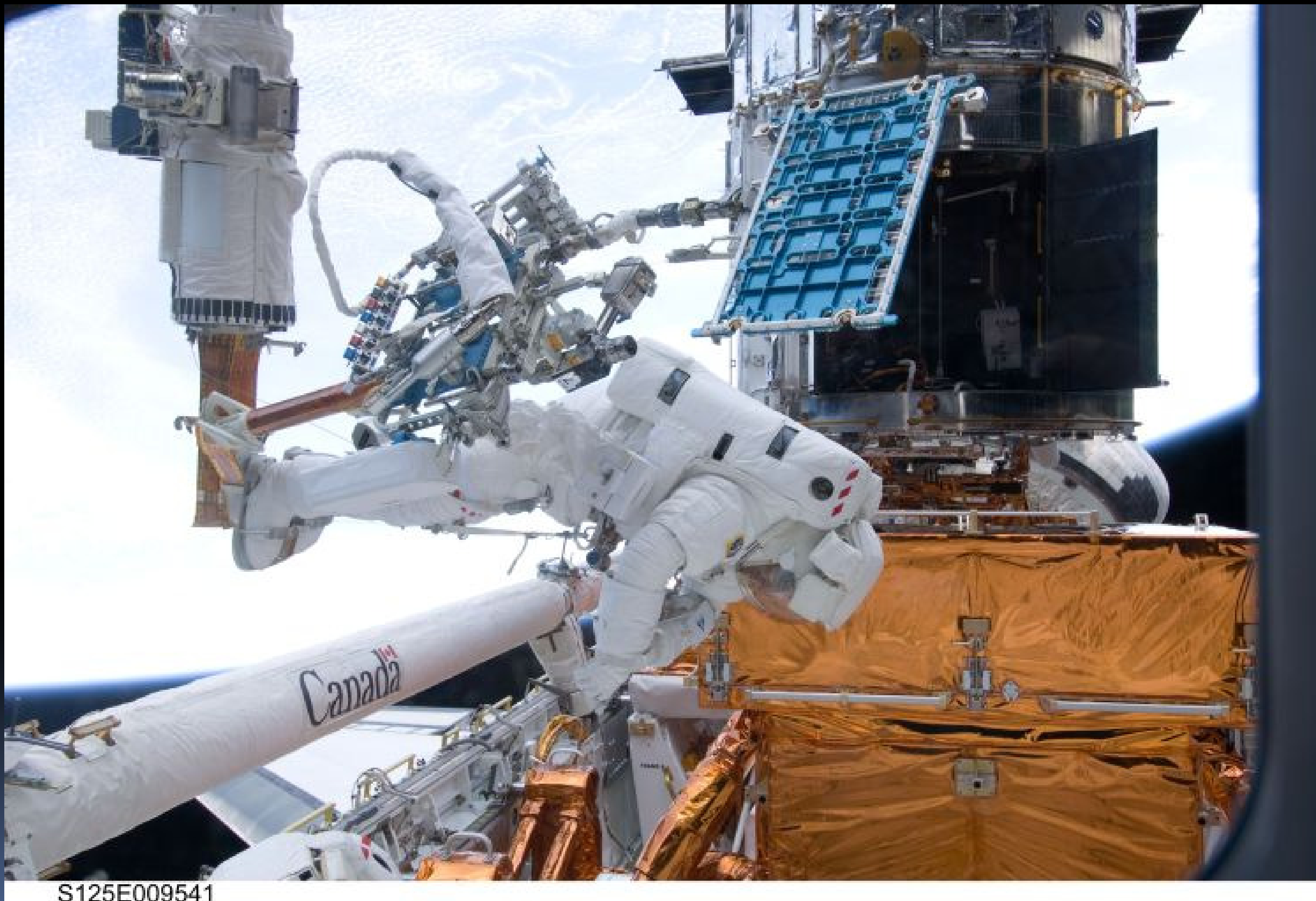
- RSU access was deemed so difficult for the robotic mission that it was decided to completely rehost them and their interface electronics onto WFC3



Interfaces Lessons Learned

- An interface that by design is difficult to install will never get easy no matter how hard you work at it or how many times you do it
- Interfaces that are designed to support servicing also facilitate integration and test
- The goal should be to make it…

TOOLS



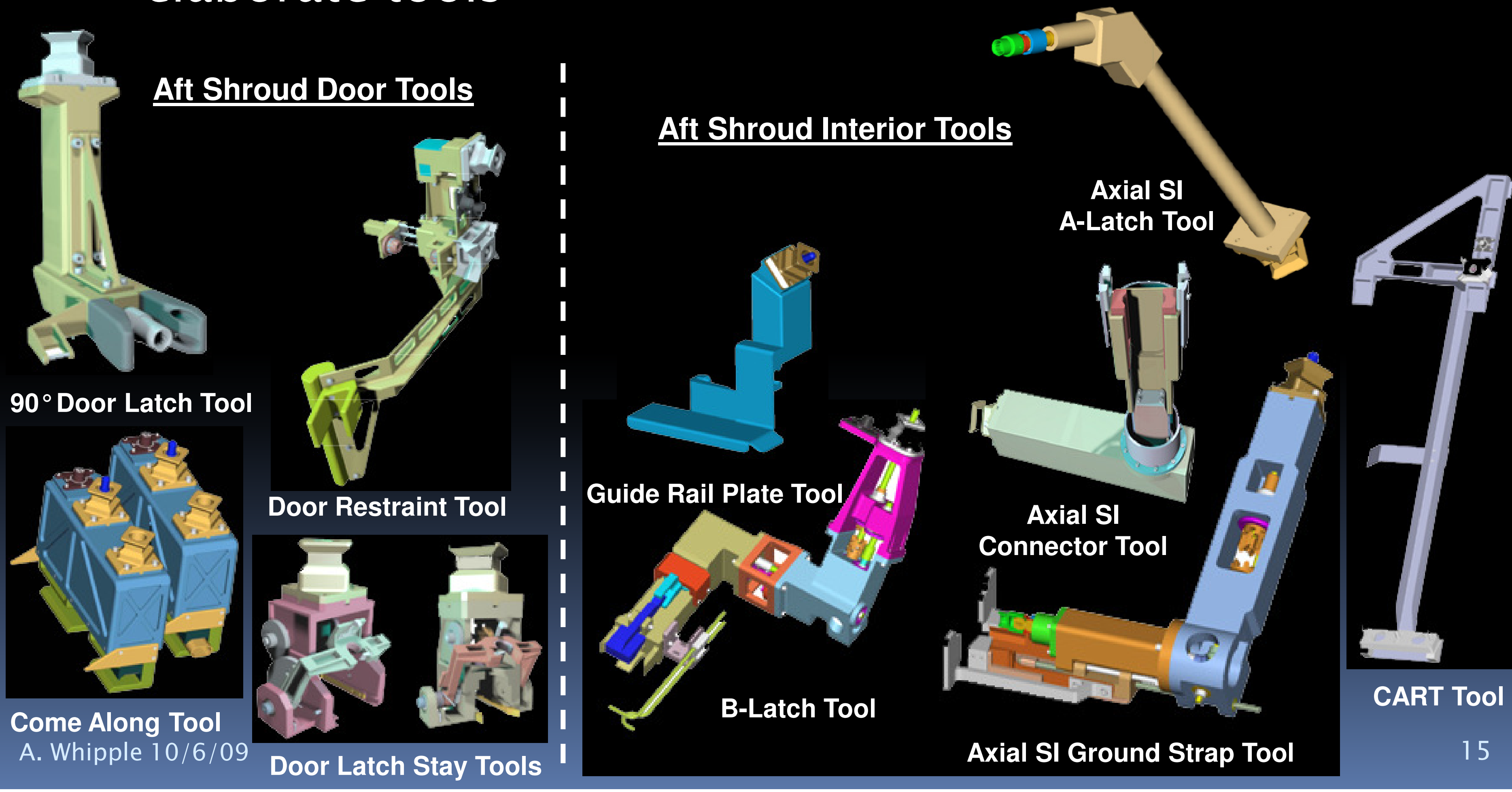
Tools used for the STIS repair on STS-125

COSTAR/COS STS-125 Tools

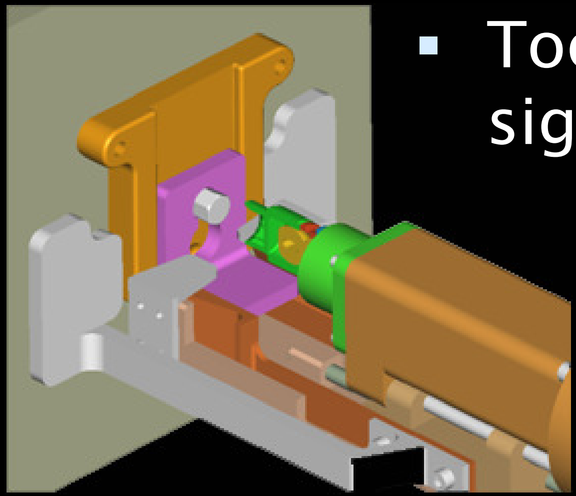
- COS change-out by EVA required 3 tools
  - Pistol Grip Tool with short adjustable extension
  - EVA ratchet with 6” rigid extension
  - Y-harness Restraint Tool
- Somewhat more complicated tools were required to accomplish the same task robotically…

COSTAR/COS HRSDM Tools

- Number and complexity of HRSDM tools was driven by requirement to employ an already flight qualified robot
- A more capable robot would have required less elaborate tools

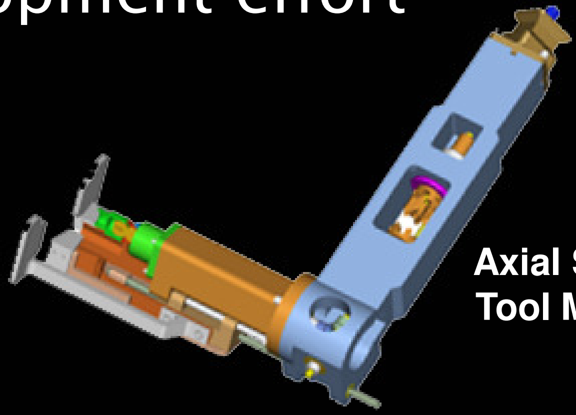


HRSDM Axial SI Ground Strap Tool

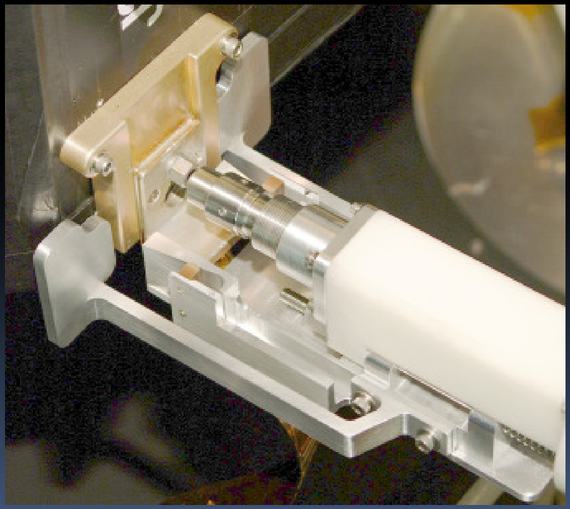


Axial SI Ground Strap Tool Workspace Model

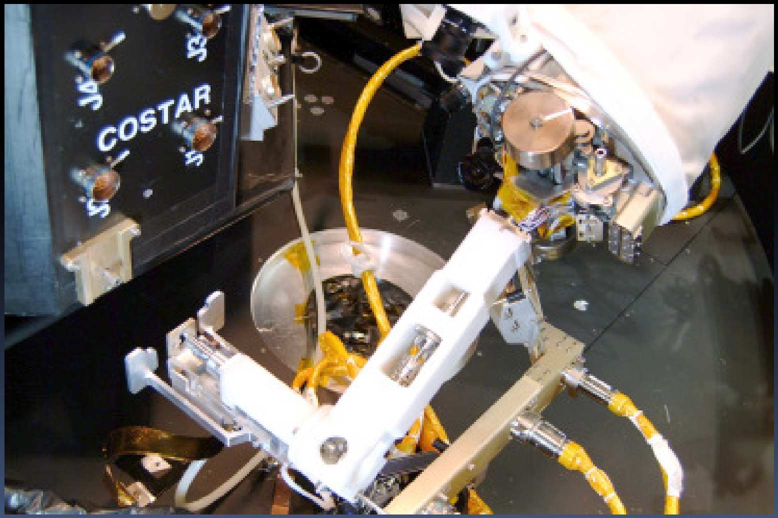
- Tools this complex require a significant development effort



Axial SI GS Tool Model



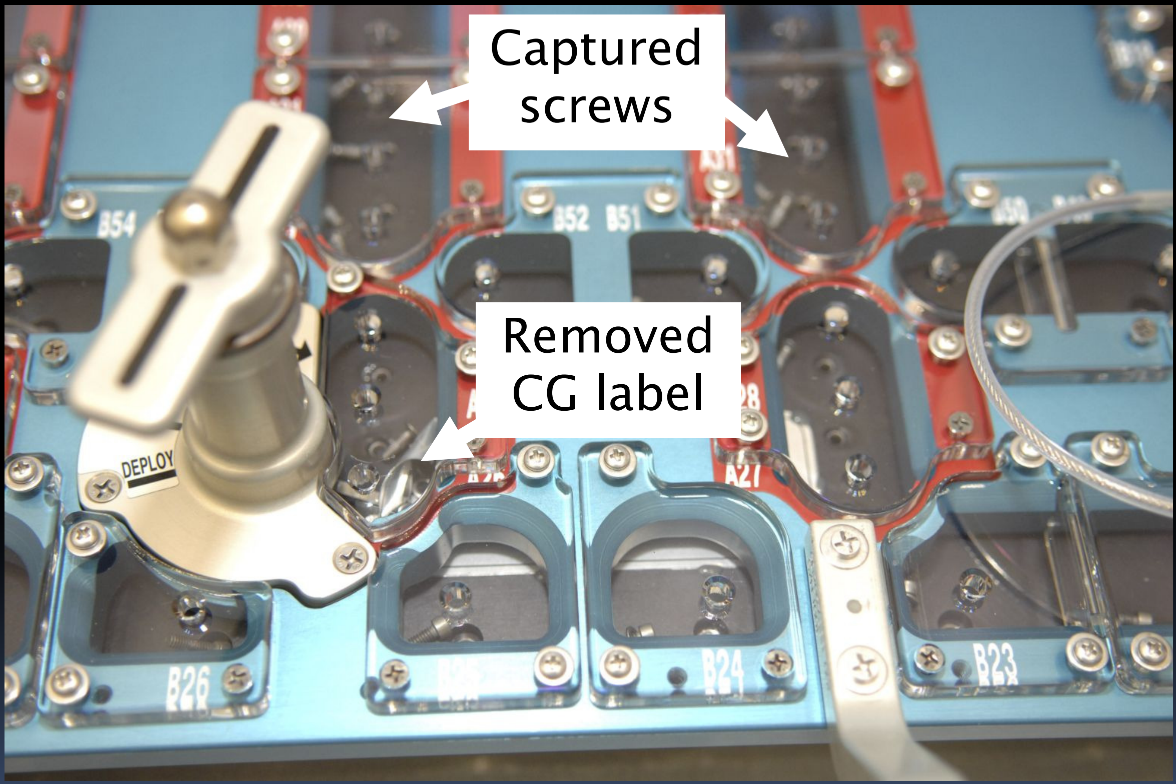
GT OTCM Manipulating Axial SI Ground Strap Tool to Engage Ground Strap Bolt



GT OTCM Manipulating Ground Strap using the Axial SI Ground Strap Tool

STS-125 STIS Fastener Capture Plate

- STIS and ACS repairs made possible by an ingenious tool invented by Jason Budinoff and initially developed by 540/Swales STIS Cover Repair Tool robotic team
  - Scott Schwinger
  - Pat Bourke
  - Jason Budinoff
  - Caner Cooperrider
  - Corina Guishard
  - Carlos Hernandez
  - Alphonso Stewart
  - Kurt Wolko



Tools Lessons Learned

- The Robot vs. Tools capabilities trade is a major consideration for robotic servicing
- Design and testing of robotic tools reinforced the value of specialized tools for <u>human</u> servicing
  - This may seem obvious given how ground-based work is done but…
  - It is a subtle trade that needs to be done carefully when mass, volume, cost, schedule, and training time are constrained
- The large number of specialized tools built for and used on STS-125 were a major contributor to the amount of servicing that was accomplished
  - 55 Reflown, 7 Modified, 97 New

MISSION DURATION



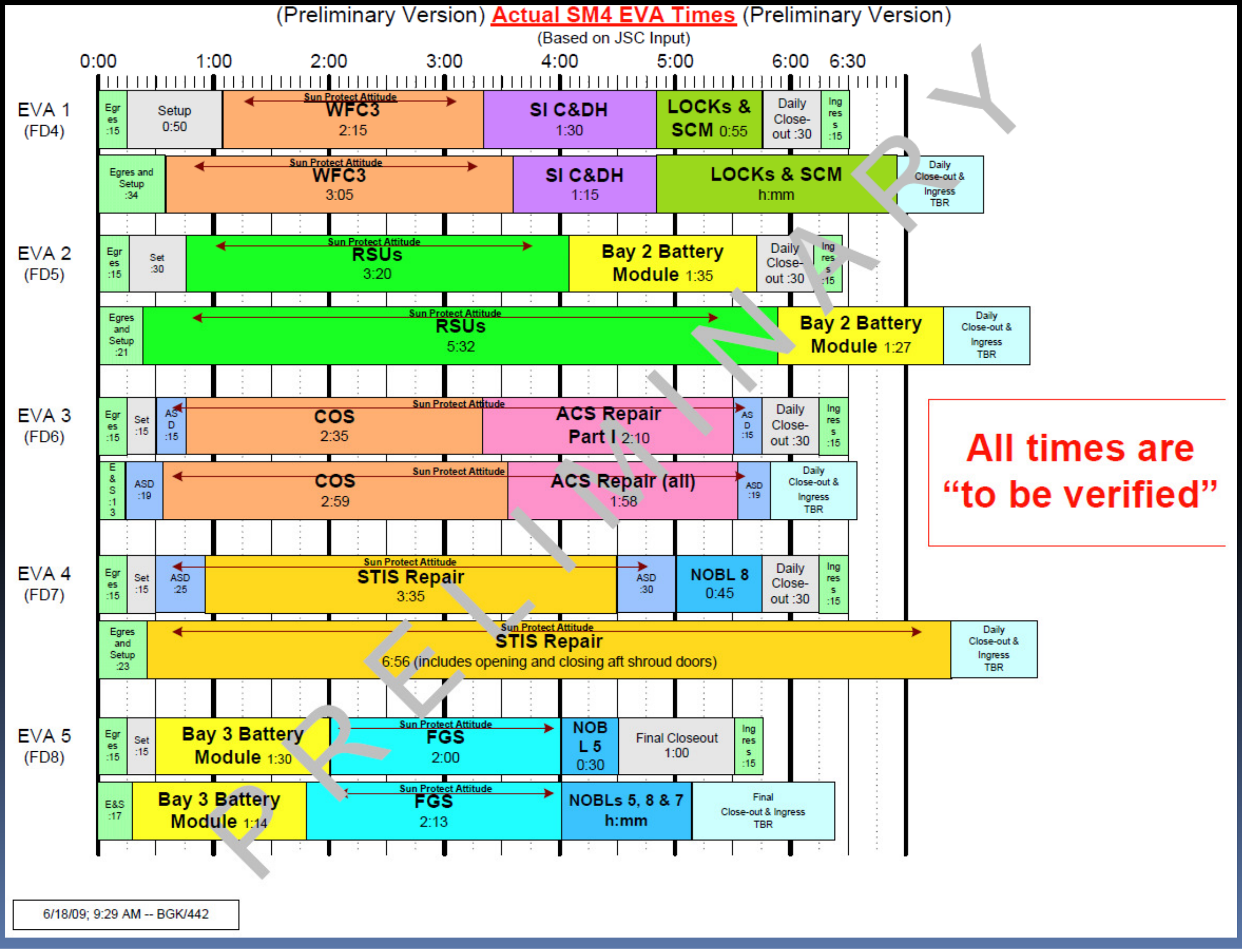



It takes a village… (actually a small town)

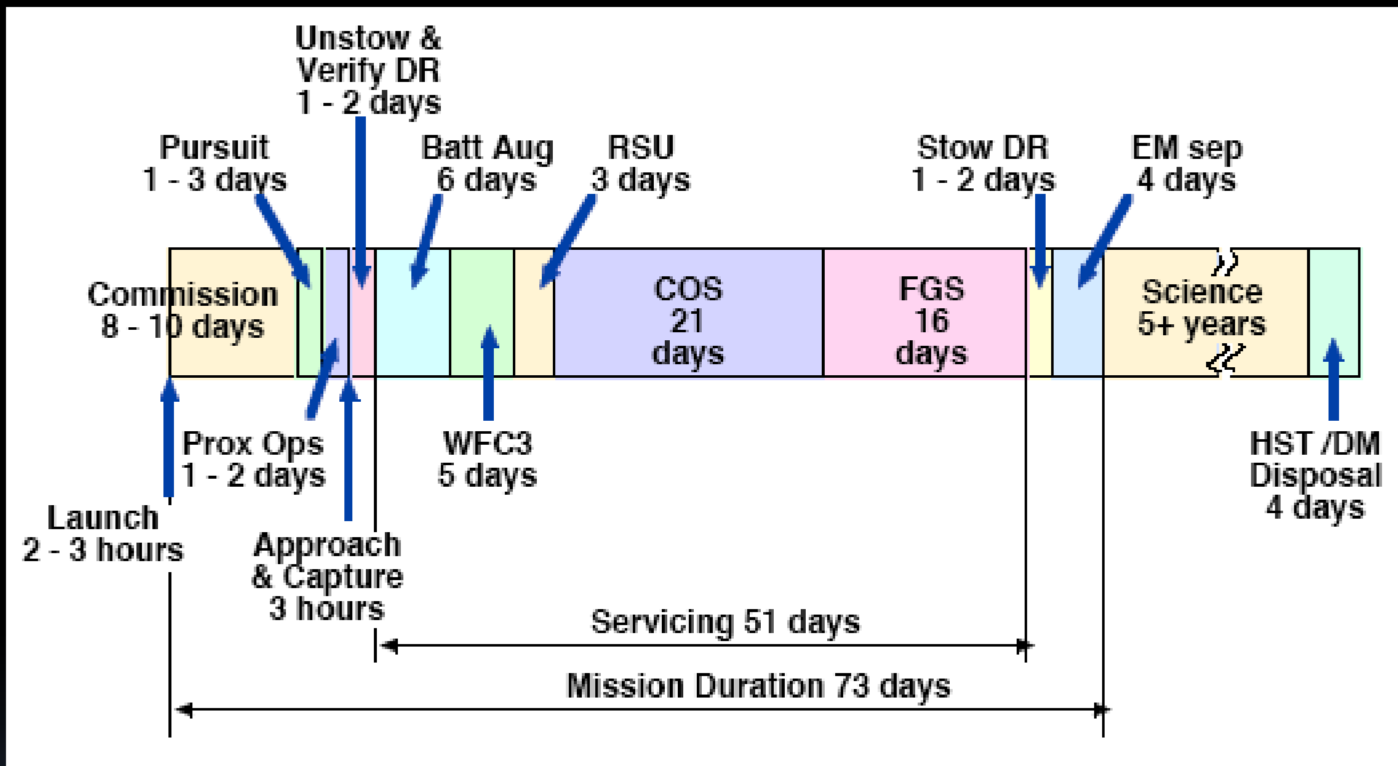

STS-125 astronauts
credit: Michael Soluri

STS-125 EVA Timeline

- Pre-launch and as-executed times shown
- Accuracy of predicts due to extensive simulation and training (NBL and 1-g)
- All significant differences due to anomalies



HRSDM Timeline



- Preliminary task execution time duration estimates shown
- We still needed to identify stable states to partition tasks to be compatible with scheduling and resource (e.g. power and thermal) constraints

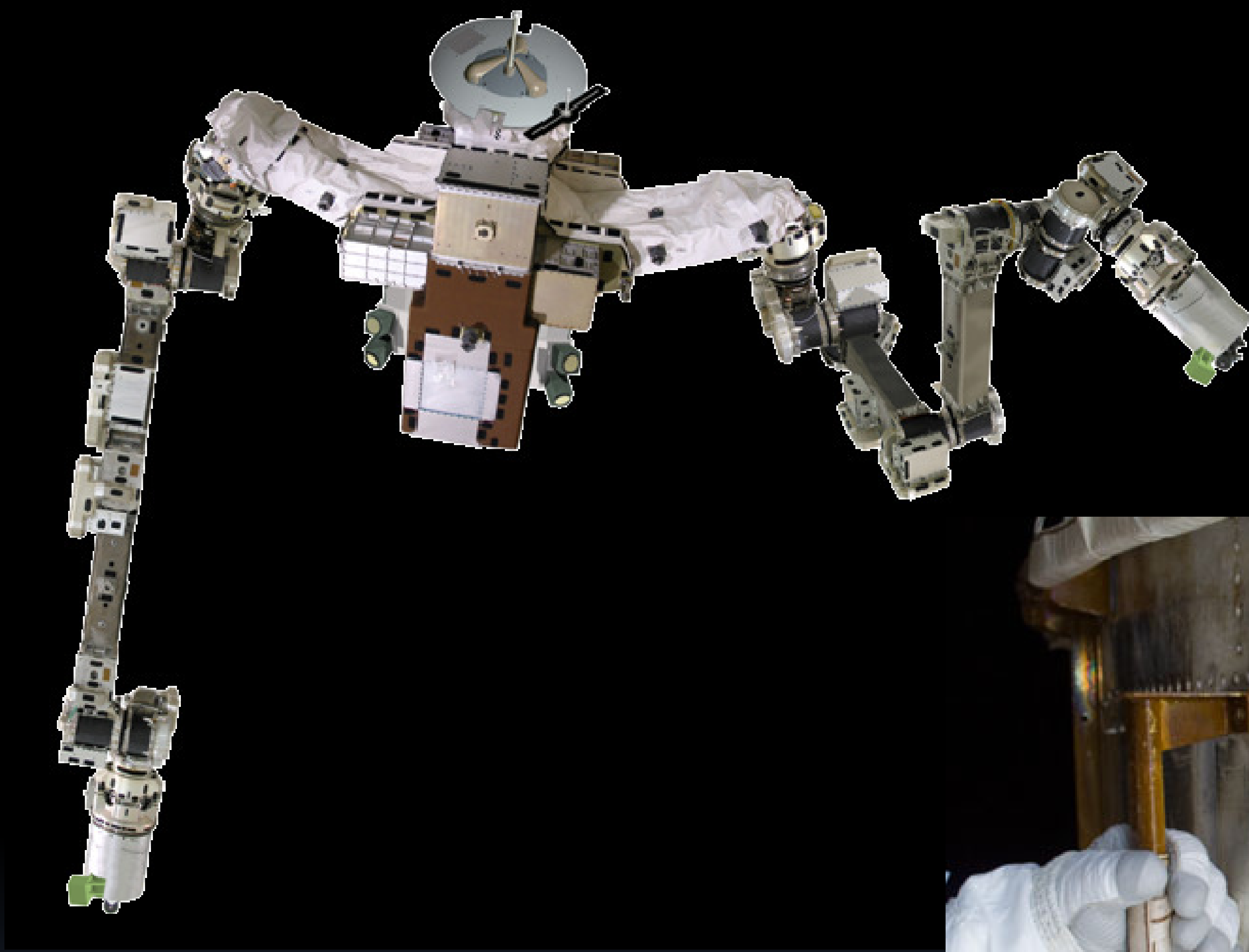
Another Recent Experience with Mission Duration

- "What Spirit and Opportunity have done in 5 1/2 years on Mars, you and I could have done in a good week. Humans have a way to deal with surprises, to improvise, to change their plans on the spot. All you've got to do is look at the latest Hubble mission to see that."
  - Steve Squyres, lead scientist Mars Exploration Rover Project *www.space.com/news/090715-apollo11-40th-squyres.html*

Mission Duration Lessons Learned

- Human servicing time is short but efficient
- Robotic servicing time is long but less constrained in duration
  - Communication latency is a real factor in duration
- High fidelity simulation and training is essential in either case to maintain mission timeline

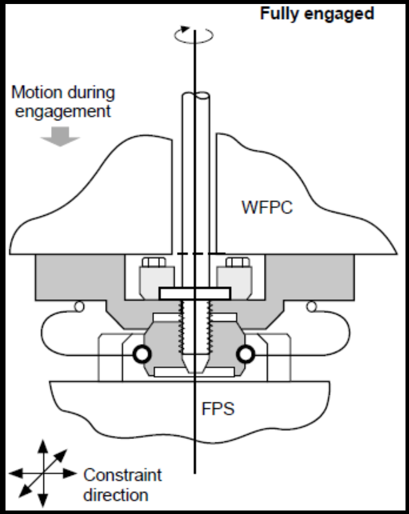
FLEXIBILITY



flex•i•ble \'flek-sə-bəl\ *adj* **1**: capable of being flexed : PLIANT **2**: yielding to influence : TRACTABLE **3**: capable of responding or conforming to changing or new situations

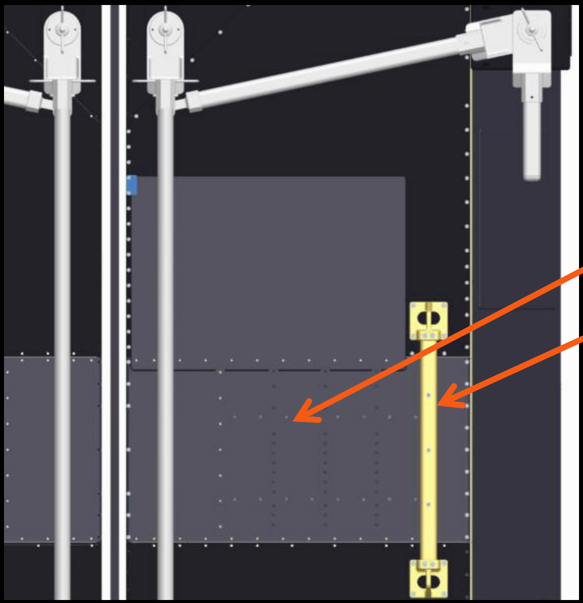
Webster's New Collegiate Dictionary

WFPC2 A-latch Anomaly



- Background
  - Breakaway torque is nominally 32-35 ft-lb
  - Failure threshold is 57.1 ft-lb (with FS=1.0)
- STS-125 (EVA1)
  - Multi-setting Torque Limiter (MTL) slipped at nominal setting of 38 ft-lb
  - Followed pre-planned EVA Cribsheet:
    - No joy using Contingency MTL at 45 ft-lb
    - Success with direct ratchet (no MTL)
- HRSDM
  - HST Extension Tool was designed to deliver max torque of 88 ft-lb
  - HRSDM tools generic force/torque margin requirement was 100% of nominal at the actuator

STIS Handrail Anomaly

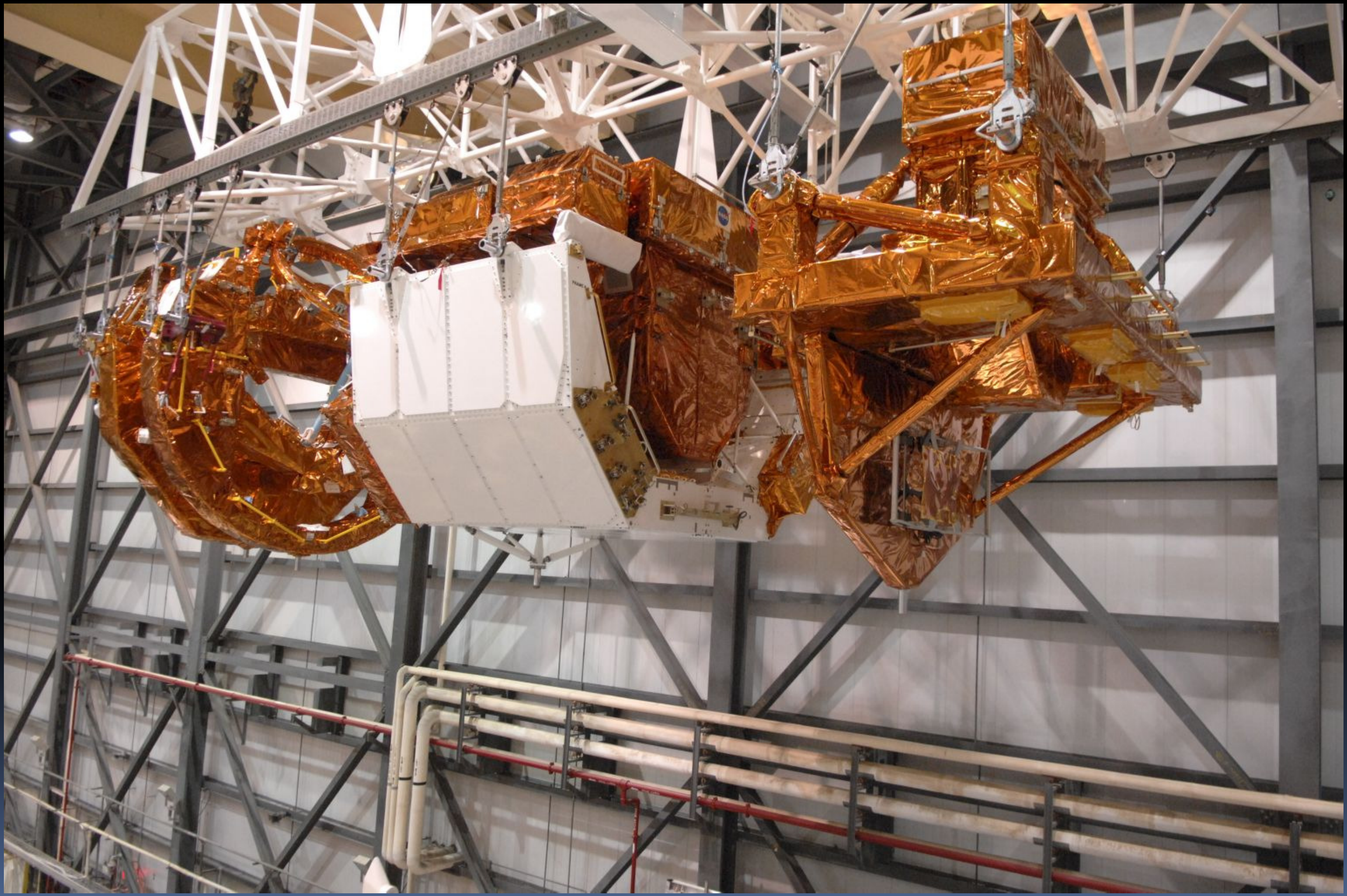


- To remove this cover
- You have to remove this handrail
- To remove the handrail you have to remove these ¼-28 staked socket head cap screws
- If the tool isn't fully engaged in the socket then damage can occur
- That's when flexibility in the "responding to new situations" sense is important

Flexibility Lessons Learned

- Design in adequate margin
- Develop robust contingency products before launch
- Mechanical flexibility in a robot can be controlled more readily than with humans
- Humans are more readily able to respond to changing situations

ADAPTABILITY



HST SM-4 Payload

Differences Between HRSDM and STS-125 Manifests

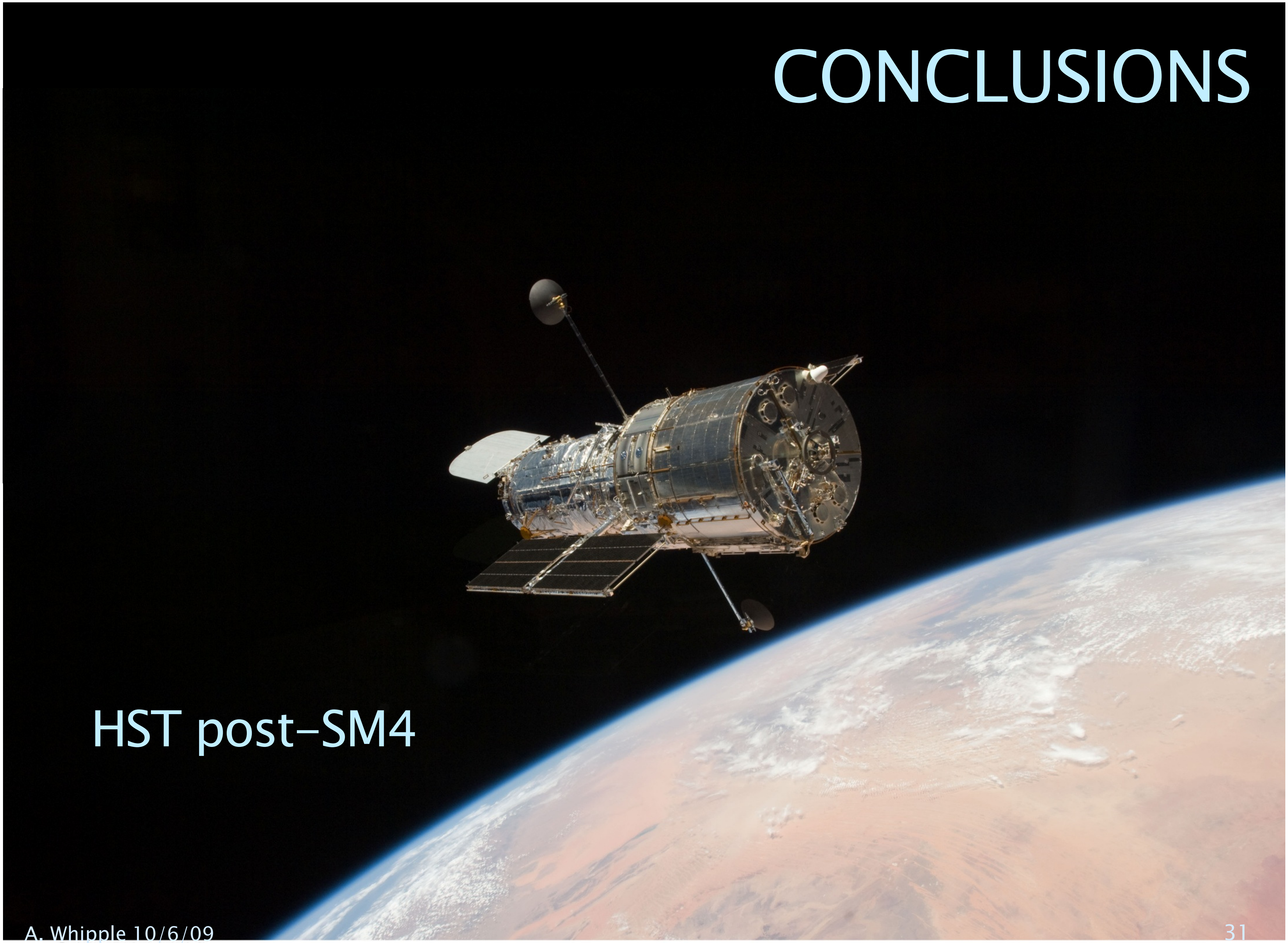
- NOBLs 5 & 7 – Carried on STS-109 (SM3B) but not high enough priority to be included in HRSDM
- STIS repair – STIS failed in August 2004, at the definition stage of HRSDM. Task was determined to be doable robotically but judged too difficult/expensive relative to science return
- ACS repair – ACS failed in January 2007. Task was harder than STIS-R because of access and number of cards to be replaced
- SI C&DH replacement – SI C&DH failed in September 2008, three weeks before planned launch. Payload accommodations and tools were more manifest specific for HRSDM than for shuttle

Manifest Comparison

		STS-125			HRSDM	
Manifest Item	**Priority**	**Minimum Mission Success**	**Full Mission Success**	**Human Score**	**Manifested**	**Robotic Score**
RSUs	1	Yes		19	Yes	19
WFC3	2	Yes		19	Yes	19
SI C&DH	3	Yes		13	No	0
COS	4	Yes		13	Yes	13
BATTERY MODULES	5	Yes		13	Yes	13
STIS OR ACS REPAIR	6		Yes	7	No	0
FGS2	7		Yes	7	Yes	7
REMAINING INSTRUMENT REPAIR	8			4	No	0
NOBL INSTALLATION	9			3	No	0
INSTALL SCM	10			2	Yes	2
Total				**100**		**73**

- HQ and JSC approved Mission Success Criteria and Manifest Priorities enable objective weighting of manifest items
- Total manifest score normalized to 100 for STS-125
- Conclusion: Productivity of a robotic Hubble servicing mission would have been about three quarters of the human mission, *assuming it was 100% successful*

CONCLUSIONS



HST post-SM4

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Thinking about Robots vs. Humans

- How robots are used on the ground?
  - For repetitive tasks where they are more economical and reliable than humans (e.g. painting, welding, circuit board assembly)
  - To extend human capabilities (e.g. cranes and micro-surgery)
  - To work in environments where humans cannot (e.g. nuclear reactors)
- We should use the same criteria to objectively guide our use of human servicing, hardwire robotics, telerobotics, and autonomous robotics

Examples of this Trade

- If the mission is a delicate one-off job like repairing ACS or a rapid turn-around job like replacing the SI C&DH then human servicing is probably most efficient
- On the other hand, the same repair at Sun-Earth L2 would have to be done robotically because of current limits on human spaceflight
- Assembling ISS modules requires robots (cranes) to extend human strength and, with people on-site, hardwire robotics is the simplest/fastest/cheapest/most reliable approach
- Relatively simple, repetitive, and long-duration jobs like communications and observing are ideally suited for (semi) autonomous robots, even in LEO where access is better
- Assembling a large structure with hundreds of identical members, regardless of location, might well justify a robotic approach due to economies of scale (repetition and duration)

Parting Thoughts

- The solution to the Working in Space problem is a continuous and evolving spectrum from EVA to autonomous robotics and *any* a priori choice would be wrong
- We need the full spectrum of capabilities and we need to apply them appropriately to the problems at hand